# RESPONSES OF THE PLANARIAN, DUGESIA, AND THE PROTOZOAN, PARAMECIUM, TO VERY WEAK HORIZONTAL MAGNETIC FIELDS [1]

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The question of whether living things are sensitive to terrestrial magnetism has undoubtedly fleeted through the minds of innumerable persons since this geophysical factor first became known. But neither the naturalist, observing the behavior of organisms in the field during their continuing responses to the myriads of more obvious physical factors, nor the experimental biologist, casually testing the response of living things to artificial magnetic fields, even very strong ones, found any consistent evidence that living creatures perceived this weak terrestrial force. It is a common observation that animals in nature may come to bear at any given moment apparently all possible compass relations in their bodily orientation; orientation of the normal resting or foraging animal to the horizontal component of magnetic field would be expected generally to be of no adaptive consequence.

In recent years, however, two kinds of phenomena have come to the forefront in biological research which are exceedingly difficult, in some instances impossible, to account for in any orthodox physiological terms. These two phenomena are the apparent persistence, in rigorously controlled constancy of all the more obvious factors of the physical environment, of biological senses of time and space in their terrestrial relationships. The first includes the mechanism for timing the well-known persistent daily, tidal, monthly, and annual periodisms. The second involves the still completely mysterious "map sense" or capacity to localize position in space which is so evident in a wide spectrum of kinds of animals capable of "homing."

Also demanding a rational explanation is the means by which organisms, even when screened from fluctuations of every obvious weather-related factor, still display variations in metabolic rate, even of quite substantial magnitudes, correlated with the essentially aperiodic weather disturbances (Brown, 1959, 1960). There remains no reasonable doubt that organisms are sensitive to some subtle geophysical factors which pervade the ordinary "controlled" conditions of the physiology laboratory. Fluctuations in these unidentified factors must bear information related to weather changes, as well as to terrestrial time and space.

In a series of recent experiments, it has been demonstrated that the marine mud-snail, *Nassarius obsoletus,* is able to perceive small changes in strength of the horizontal component, H, of a magnetic field close in strength to that of the earth's natural field (Brown, Brett, Bennett and Barnwell, 1960; Brown, Webb and Brett, 1960; Barnwell and Webb, 1961). The snail can, furthermore, distinguish between directions of the fields, both the earth's and weak ones produced by bar magnets

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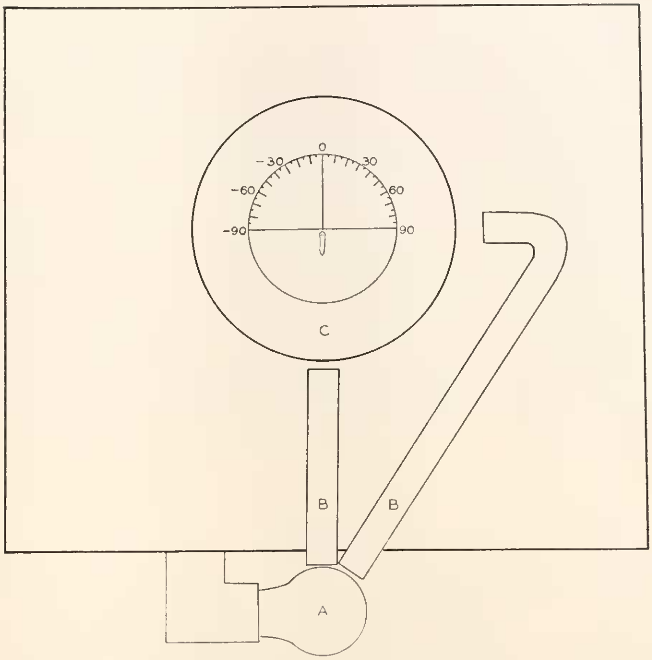


FIGURE 1. The apparatus employed in the study of response of *Dugesia* to magnetism, showing arrangement of (A) 7½-watt opalescent lamp; (B) sleeved light-conducting glass tubes; (C) Petri dish centered over a polar coordinate grid.

(Brown, Bennett and Webb, 1960; Brown and Webb, 1960; Brown, 1960; and Brown and Barnwell, 1961). The character of the response to magnetic field exhibits rhythmic changes that are regulated by the solar-day and lunar-day "clocks" of the snails, and by a synodic monthly one. The following study was conducted to learn whether such responsiveness was of wider biological distribution.

## METHODS AND MATERIALS

The common, small flatworm, *Dugesia dorotocephala,* was selected as an animal possessing convenient behavioral characteristics for study, and simultaneously being non-marine and phylogenetically very distantly related to the snails. The worms were collected twice a year, in early October and in June, from a small spring-fed stream in Fox River Grove, Illinois. They were maintained in darkened containers in the laboratory, and fed liver twice weekly.

The apparatus consisted of a 3¾-inch glass Petri dish centered over a polar coordinate, paper grid (Fig. 1). This apparatus was set inside a black-lined wooden cabinet; use of ferromagnetic materials was carefully avoided in the whole assembly. The apparatus was continuously illuminated from a 0.5-inch circular source about 16 inches directly above the center of the grid, provided with a 7½-watt opalescent lamp which yielded an illumination of about five lux at the Petri-dish level. A second small light provided a weak horizontal source of illumination parallel to the zero axis of the grid, and a third, horizontal weak light source provided illumination parallel with the 90° axis, from the right side. The horizontal light sources were onion-skin paper-covered ends of black-sleeved, 10-mm. solid glass rods leading light into the cabinet from a 7½-watt opalescent lamp attached rigidly to the outside of the cabinet. To minimize other, uncontrolled illumination sources, the experiments were conducted in a darkened room.

In operation, a planarian was quickly oriented with a fine brush toward the zero axis of the polar grid, just short of its origin, as illustrated in Figure 1. The deviation in worm path from the initial direction was then recorded in terms of the point, to the nearest 5°, at which the worm crossed the circular arc one inch from the origin. Measurement of the times to reach the one-inch line was found for 22 paths to average 15.45 seconds; standard deviation was ±2.02 seconds. There were no obvious orienting cues in the system other than the two horizontal light sources. The single vertical light source provided no cue. Any unintentional bias due to asymmetry of any other factors, such as extraneous reflected illumination, remained essentially unchanged throughout the period of experimentation.

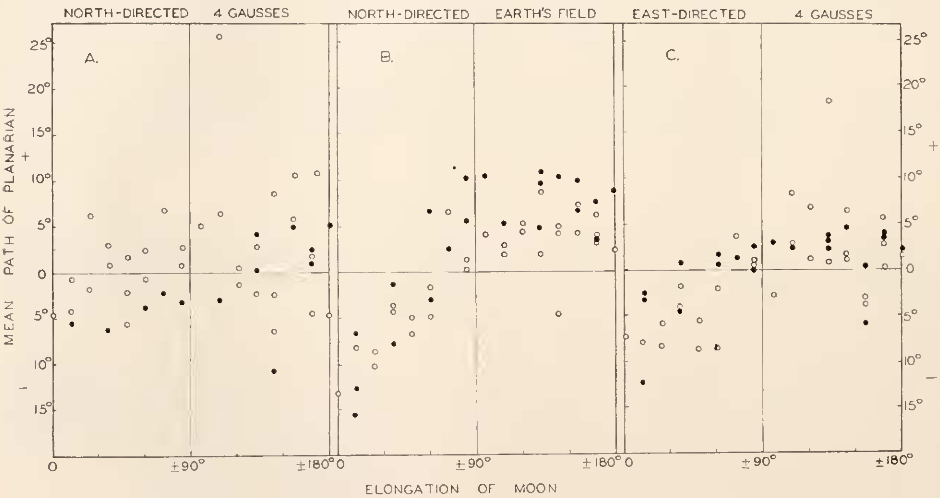


FIGURE 2. The mean angular path of initially N-directed planarians as a function of elongation of the moon (0° = New Moon; 180° = Full Moon); with (A) a North-oriented magnetic field of 4 gauss, (B) the earth's field alone and (C) an experimental field of 4 gauss, with South pole directed Eastward. Solid circles, first experimental series (November and December); open circles, repetition of experiment (January).

Beneath the apparatus were calibrated slots into which an 18-centimeter Alnico bar magnet could be placed horizontally at distances to produce any one of a series of horizontal field strengths, with the south pole rotatable to any desired compass direction to supplement, subtract from, or otherwise modify, the natural horizontal field.

It should be recalled at this time that by convention of physicists, the earth's northern pole is a magnetic S pole and the southern pole, a magnetic N one.

ORIENTATION OF NORTH-BOUND WORMS IN A SINGLE, VERTICAL-LIGHT FIELD

During about a two-month period from November 8, 1960, through January 2, 1961, 4677 planarian paths were recorded,[2] 2172 in the earth's field alone and 1766 in a four-gauss field, with the S pole directed East. The apparatus was at all times directed magnetic north. A single horizontal light, that one parallel to the zero axis of the grid, was used. It was left on only until the moment the worm reached the origin. It was then extinguished. The observations were made on about 24 occasions, never more than one series on any given day, distributed over the whole period. In very few cases, with too small sample sizes on a given day, the data were combined with those of the succeeding day. The observations were always made sometime between 9 A.M. and 3 P.M., to minimize any daily rhythmic change that might occur, comparable to that previously demonstrated for the snails. For each sample series 45 to 140 paths were recorded for each in the earth's field alone and in the E-W four-gauss experimental field.[3] On six occasions over the period November 25 through December 3, and on seven occasions from December 19 through January 2, each observational series included the recording of paths under three conditions. These were in the aforementioned two fields, and now, in addition, in a four-gauss field with the S pole directed north. This last field augmented the earth's natural 0.17-gauss north-directed horizontal one. The total number of paths observed in the N-S field was 739.

TABLE I

*Planarian paths*

| Date | No magnet | | | E. W. magnet | | | N. S. magnet | | |
|---|---|---|---|---|---|---|---|---|---|
| | N | Mean | σ | N | Mean | σ | N | Mean | σ |
| Nov. 25–6 | 82 | +10.00 | 38.2 | 85 | +2.60 | 25.0 | 85 | − 3.24 | 35.1 |
| Nov. 28 | 83 | + 9.50 | 32.2 | 59 | +2.55 | 23.1 | 53 | + 4.06 | 39.9 |
| Nov. 29 | 51 | +10.20 | 29.6 | 46 | +4.80 | 26.5 | 55 | −10.45 | 43.7 |
| Nov. 30 | 98 | + 6.42 | 36.2 | 77 | +0.58 | 25.6 | 89 | + 5.17 | 39.4 |
| Dec. 1–2 | 140 | + 8.03 | 33.4 | 72 | +2.43 | 19.9 | 77 | + 5.20 | 47.0 |
| Dec. 3 | 57 | + 5.80 | 36.6 | 47 | +3.51 | 22.4 | 54 | + 2.32 | 35.7 |
| | σ Range 29.6 − 38.2°<br>M = +8.25 ± 1.53°<br>σ = 34.6 ± 1.08° | | | σ Range 19.9 − 26.5°<br>M = +2.68 ± 1.22°<br>σ = 24.0 ± 0.87° | | | σ Range 35.1 − 47.0°<br>M = −0.85 ± 2.00°<br>σ = 40.6 ± 1.42° | | |

[2] The author wishes to acknowledge his indebtedness to the several persons, especially to Young H. Park, Bertil S. Thunstrom, and Andrew Bertagnolli, who devoted many hours to acquiring the data of this study.

[3] The stated horizontal field strengths in this report are the fields present at the level of the worms when the bar magnet is oriented to oppose the earth's own horizontal vector and differs from these in the expected manner as it is rotated to other directions in the earth's 0.17-gauss field. The values are accurate only to about ±10% as a consequence of pole-strength variations among the individual magnets employed. The field strengths were initially computed, but later were confirmed with a Rawson gaussmeter.

A second and more systematic study, involving 3493 worm-paths, 1186 in the earth's field, 1181 in the N-S, and 1126 in the E-W magnetic fields, was conducted between December 28, 1960, and January 31, 1961. There were 29 observational series, involving 29 different days; each series included observations under each of the three conditions of experimental fields.

The mean path of the worms in solely the earth's field exhibited throughout the three-month period a synodic monthly fluctuation, the worms turning maximally counterclockwise at the time of new moon and maximally clockwise over the fortnight centered on full moon. In Figure 2B, the solid circles indicate the mean path in degrees as a function of elongation of the moon (angle between sun-earth and moon-earth axes) for the worms in the earth's field for the first experimental study, and the open circles for the repetition of the experiment, or second study. In Figure 2C are the mean paths at the same times as measured for the four-gauss E-W experimental field, and in Figure 2A for the N-S experimental field. In every

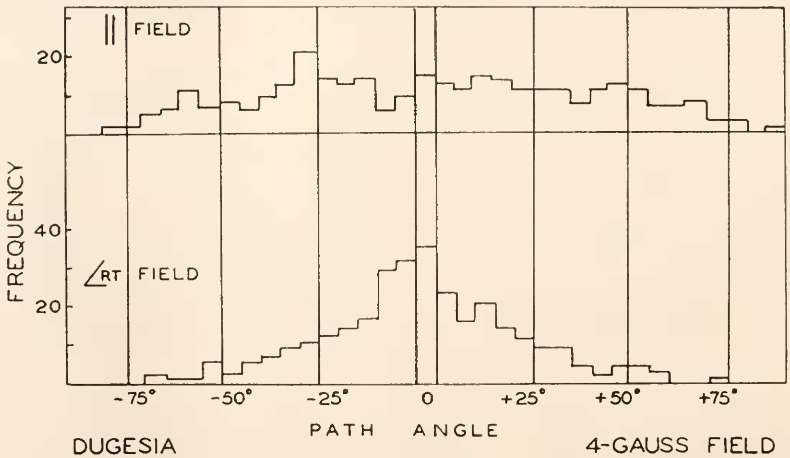


Figure 3. Frequency distributions of planarian paths in the 4-gauss N-S field (upper) and E-W field (lower), during the period November 25–December 3, 1960 (see Table I), a period during a late autumn full-moon semi-month.

single daily series in the first set of experiments, when the worms were turning clockwise in the earth's field, the experimental E-W field effected less clockwise turning, and when the worms were turning counterclockwise, the E-W field effected less counterclockwise turning. This is illustrated, in part, in Table I for the relatively stable values obtained during the full-moon semi-month, November 25–December 3.

The worms were apparently able to distinguish between the E-W and N-S four-gauss fields on the one hand, and between either of these and earth's field on the other, as is evident both from inspection of Figure 2 and from the statistical analyses shown in Table I. In Table I, it is seen that the mean paths of the worms in the E-W and N-S fields were not significantly different from one another, but the standard deviations were clearly so. The increased standard deviation in the N-S field over the E-W one reflected a conspicuous increase in turning, but now both clockwise and counterclockwise. The effect is evident from comparison of the two frequency distributions in Figure 3.

The planarian orientational response in the earth's field alone appeared, during this study, to be a function of elongation of the moon, over nearly three 360° cycles. The relationship seemed to be roughly symmetrical about 0°. The limits of clockwise and counterclockwise response appeared, within the error of measurement, to be phase-synchronized with the upper and lower lunar transits.

From Figure 2, it is evident without need of recourse to statistical analysis that the monthly cycle, so obvious in the earth's magnetic field alone, was partially suppressed by the 4-gauss E-W field, and abolished by the 4-gauss N-S one.

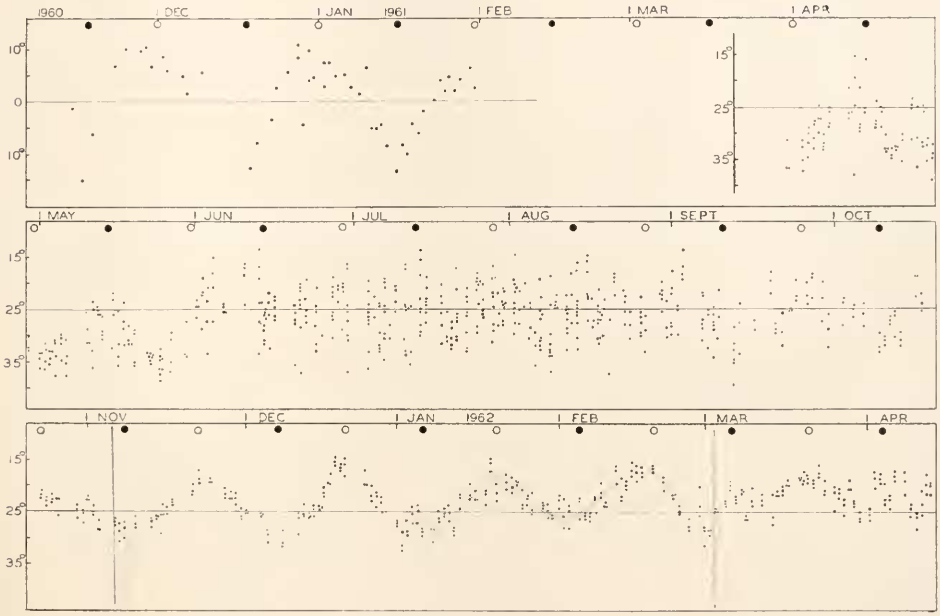


FIGURE 4. Variations in the character of the monthly orientation rhythm of *Dugesia* over about a 17-month period. From November through January, 1960, the worms were in a single vertical light field; each point was the average of 45 to 140 paths. For the remainder of the time, the worms were in a three-light field with each point the average of 15 paths.

## MONTHLY RHYTHM IN NORTH-BOUND WORMS

The monthly variation in the path of the North-directed planarians during late morning and early afternoon hours was followed for more than an additional year. Data were obtained from late March through August by sorting out the numerous control samples of North-bound worms in the earth's field alone from experiments involving responses of *Dugesia* to modified fields. The latter included (1) changes in compass direction in the earth's field, (2) rotation of a horizontal, experimental 10-gauss field while animals remained continuously magnetic-North directed, and (3) differentiation of magnetic axes of horizontal fields as related to horizontal field-strength. These latter results have been reported earlier (Brown, 1962a) in a preliminary account, but will be described in more detail below.

For all these later experiments from April, 1960, onward, the illumination was different from that of the initial experiments. The worm's orientation was observed in a steady three-light field; the three lights were at 90° to one another in the arrangement described earlier.

The mean path of the worms always involved counterclockwise turning in response to the weak light on the right. This illumination pattern was adopted because the variance of paths was found to be less. Each sample now comprised always the mean of only 15 worm paths.

In Figure 4 are shown the mean paths in degrees plotted against day of the year and phase of moon from November 10, 1960, through to April 14, 1962. The clear monthly cycle, with maximum counterclockwise turning on the day of new moon and maximum clockwise turning about the time of full moon, is again evident from November 10 through January 31. Here each point is the mean of 45 to 140 worm paths. No data including mean paths of worms North-bound in the earth's field alone were obtained between January 31 and March 31.

North-bound worms in the earth's field alone exhibited a monthly variation between March 31 and about the middle of May, but now the mean path of the worms, in the three-light field, was steadily to the left and the turning relationship to lunar phase was the mirror image of the earlier observations during the preceding late fall and winter. Scatter of the mean paths was substantially greater than during the preceding period of study.

By early June, there was a suggestion of a tendency for a maximum in clockwise turning to occur near the times of both new and full moon. By the latter part of June, the scatter of the mean paths had become even greater and continued so for three or four months. There was suggestion from inspection of the data, however, of a tendency for counterclockwise turning to be greater over the quarters of the moon than over the times of new and full moon. A quantitative analysis of the paths from June 15 to August 31 proved those for the seven-day periods centered on the moon's quarters to be $-26.48 \pm 0.384$ ($N = 157$) and those for seven-day periods centered on new and full moon to be $-24.21 \pm 0.393$ ($N = 136$). The difference between these two was highly significant ($t = 4.1$). In other words, there appeared to be a low amplitude semi-monthly fluctuation during the summer with maximum clockwise turning at both new and full moon.

By late August, there was an abrupt inversion in lunar relationship to yield a maximum in counterclockwise turning at full moon, and another near new moon early in September. There was thereafter a gradual return to a clear monthly fluctuation with maximum left turning at new moon and right turning at full moon. The monthly fluctuation became progressively more sharply defined, with scatter of mean paths reduced, between September and November. By the latter time, the overall form and phase relations of the monthly variation had become, and remained through the winter, qualitatively like those which obtained for the corresponding months of the preceding year.

By early March, there was an abrupt alteration in phase to give a maximum in clockwise turning at new moon. This inversion, which seems to have been anticipated during the preceding two months, judging from the gradual decreasingly

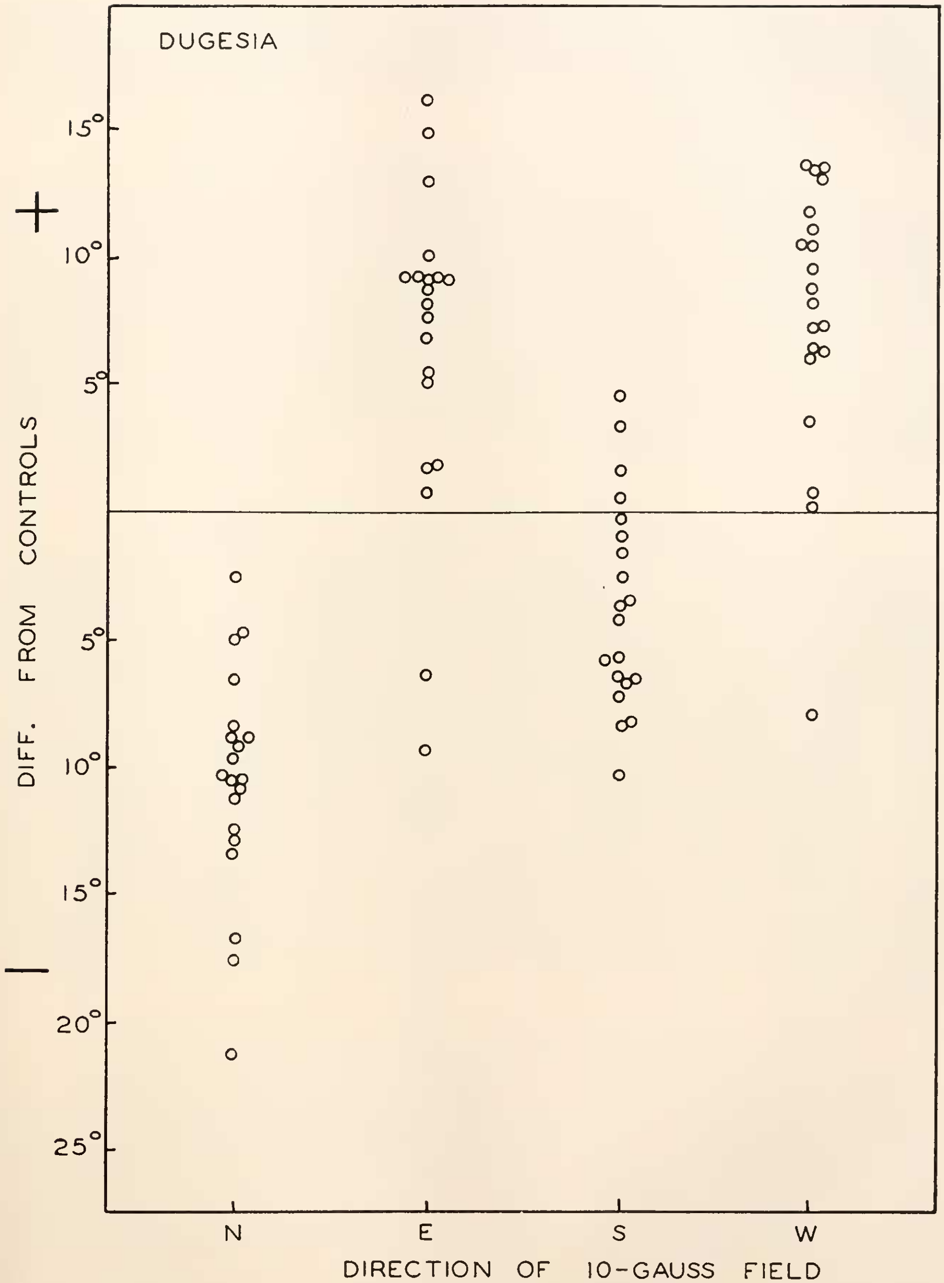


FIGURE 5. Difference between the mean paths of *Dugesia,* initially directed Northward in the earth's field, and the comparable paths when experimental, horizontal 10-gauss fields, with South-pole directed in each of four compass directions, are superimposed. Path angle is expressed as difference from interpolated controls in the earth's field alone.

strong left turning at new moon, suggested the initiation of a mirror-imaging of a monthly cycle during April to June, comparable to that observed the corresponding months of the preceding year. The variations in form of the monthly rhythm clearly suggest an annual component.

## Orientation to a Ten-Gauss Horizontal Field

Between March 31 and May 5 the response of *Dugesia* to a 10-gauss horizontal field was determined as the field was rotated by 90° intervals while the orientation apparatus itself remained steadily directed magnetic North. On 20 mornings series were run consisting of each of four directions of the experimental field, with a "control" in the earth's field alone following each 10-gauss exposure. The effects of the 10-gauss field, with S-pole directed N, E, S, and W, expressed as differences from the average path of the four controls in the same-day series, is illustrated in Figure 5. The worms clearly differentiated between parallel and right-angle fields, and between N- and S-directed fields.

## A Compass-Direction Effect in Earth's Field Alone

Another experiment with *Dugesia* was very informative. This was performed during the period from June 15 through September 12. It involved simply rotating the orientation apparatus by 90° intervals in a darkened room, in the earth's field alone. In this experiment, performed on 30 different afternoons distributed over the three-month period, each series included all four compass directions, in shuffled order, followed at once (in every instance but one) by a repeat of the four, again shuffled. When average path for each compass-direction was computed as the difference from the mean for the four directions of that particular group of four, the results shown in Figure 6 were obtained. The worms in the earth's field alone clearly distinguished between N-S and E-W orientations. However, the results obtained in the earth's horizontal field of 0.17 gauss and illustrated in Figure 6 are essentially the mirror-image of those depicted in Figure 5, which are the results from the rotation of the 10-gauss field. The significance of this difference was clarified from the results of the following experiment that was run concurrently.

## Relation of Horizontal Field-Strength to Orientation

This experimental series was run on 24 mornings distributed uniformly over the three summer months. In this one, in shuffled order but always starting and ending with a control, and with a third control midway in the series, were experimental horizontal magnetic fields of four strengths—0.25, 2.0, 5.0, and 10.0 gauss, with South pole directed North and West. Figure 7 illustrates the results obtained by taking the difference between N and W. It is clear that between the three weaker fields on the one hand and the 10-gauss one on the other, there is a reversal in relative left-turning influence. The difference between response to N-directed and W-directed fields increases with a positive sign up to some limit, as the experimental field increasingly overrides the earth's, but then abruptly adopts a negative sign somewhere between 5 and 10 gauss.

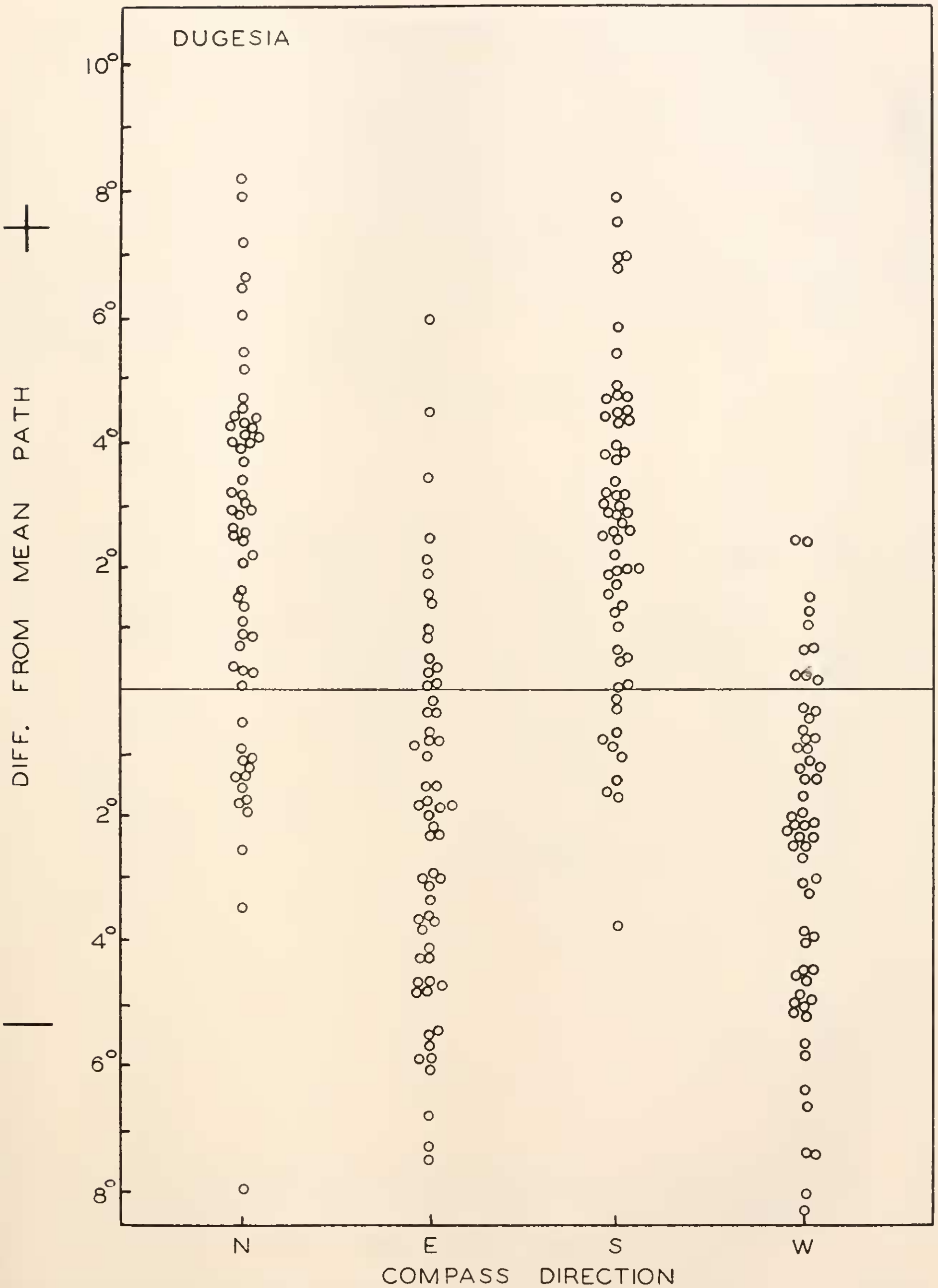


FIGURE 6. Difference between mean path of planarians for each four compass directions and the mean path in the same series for all four directions taken together, as the orientation apparatus is rotated to each of the four compass directions, in shuffled order, in the earth's field alone.

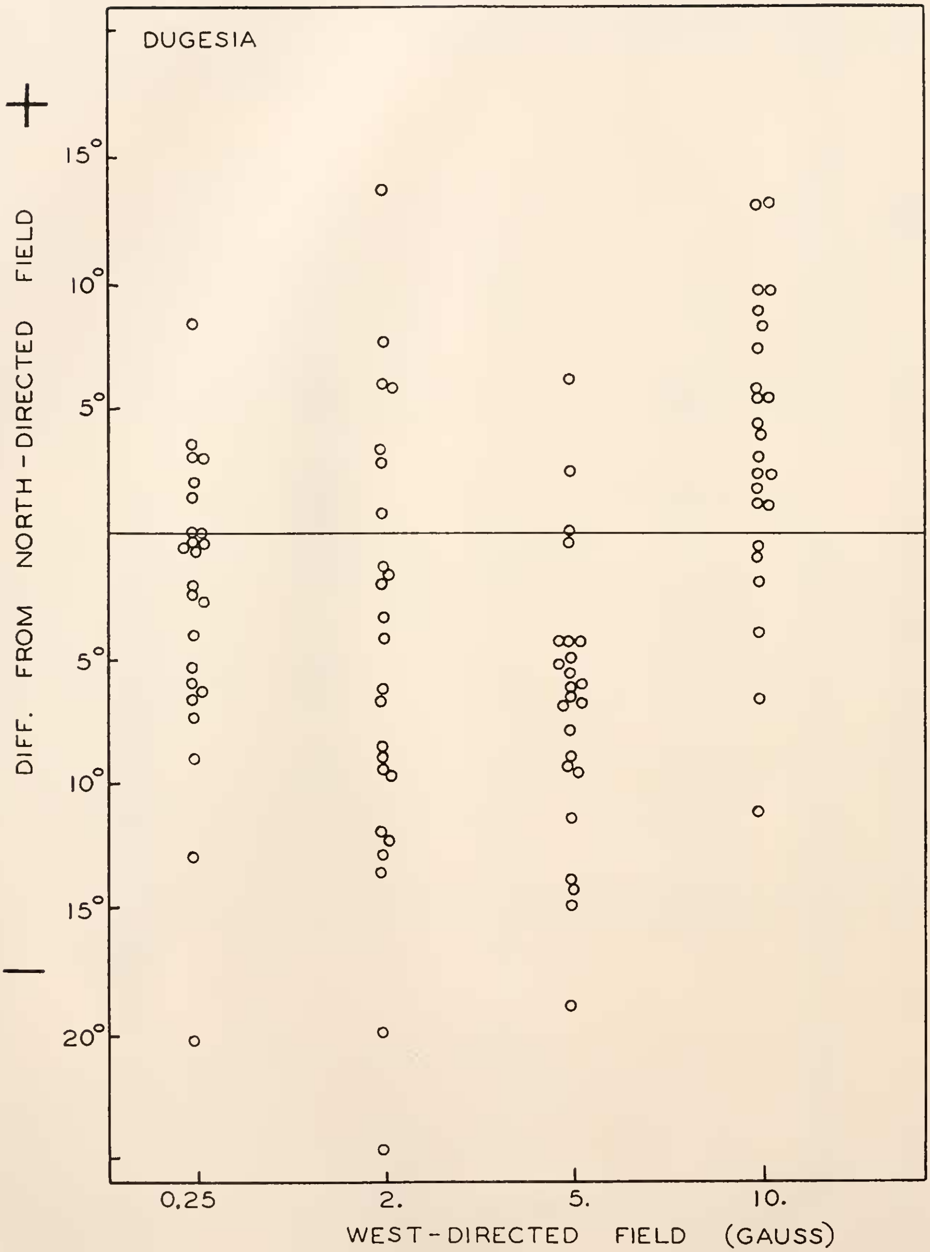


FIGURE 7. Difference between the mean paths of *Dugesia* initially directed Northward in the earth's field and simultaneously subjected to experimental N-directed fields to supplement the earth's to yield the values indicated, and the mean path resulting from rotation of the supplementing magnet 90° in a counterclockwise direction.

## Resolution of Magnetic Field Direction

One final experimental study was conducted with *Dugesia* between June 20 and August 16, 1961. Two observers were involved, working concurrently. The experiment was performed on 21 different mornings distributed over the two-month period. For each daily series 15 worms were observed moving compass-North under each of 11 conditions presented in shuffled order. The observers were wholly uninformed of the conditions which obtained at the time of their observations. The eleven conditions included seven in which a 5-gauss horizontal field was presented at each of seven orientations at 15° intervals from S-pole directed North to S-pole directed West, and four in which the magnet was removed and the worms moved North in the earth's field alone.

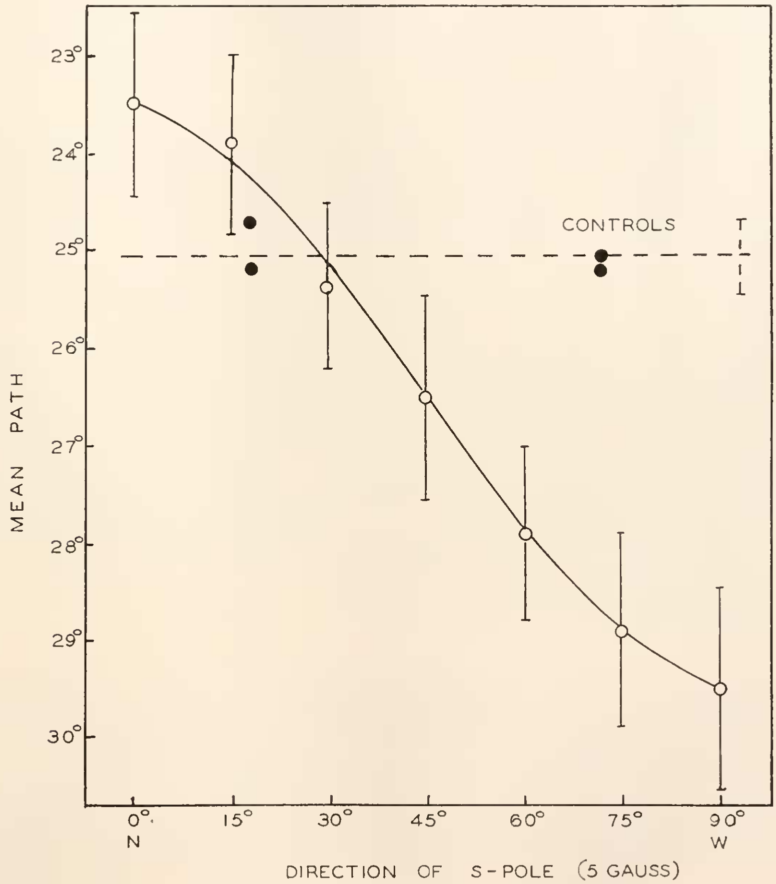


Figure 8. Open circles illustrate the relationship of mean path to magnet orientation for magnetic-N-directed *Dugesia* in a three-light field and subjected to an experimental 5-gauss field with S-pole changed by 15° intervals from North to West. The means for each of four successive controls in the series, for the earth's field alone, which were interpolated in random order in each experimental series, are indicated by the solid circles. Standard errors of the means are shown.

Table II

*Path deviations from controls on same day*

| Angle | M | S.E. | N | Variance |
|---|---|---|---|---|
| 0° | +1.50° | ±0.97 | 42 | 34.4° |
| 15° | +1.14° | ±0.76 | 42 | 23.0° |
| 30° | −0.36° | ±0.65 | 42 | 17.1° |
| 45° | −1.48° | ±0.77 | 42 | 23.6° |
| 60° | −2.63° | ±0.83 | 42 | 26.4° |
| 75° | −3.84° | ±0.78 | 42 | 24.6° |
| 90° | −4.46° | ±0.85 | 42 | 27.4° |

The mean paths of experimentals and controls for the two-month period are plotted against the conditions, in Figure 8, together with standard errors of the means. It is evident that the mean path of the worms was a function of the angle of the experimental horizontal field.

The standard errors are relatively large, in some measure a consequence of systematic fluctuations in paths of all worms, both controls and experimentals, from day to day. These latter fluctuations included a highly significant semi-monthly component. Consequently, it was not surprising to find, as shown in Table II, that when the mean paths of the experimentals were treated as deviations from the mean path for the four controls in the same series, significantly smaller errors were observed.

Two other facts were notable. As shown by Table III, the variance of the 42 mean paths in an experimental magnetic field was in every instance substantially greater than for any one of the four controls. The presence of a 5-gauss field significantly ($P < .005$) increased variance over that of controls. And whether one deals with variances of the actual mean paths (Table III) or variances of deviations from control paths (Table II), minimum variance is observed in this experiment when the worms tend to move in a path most nearly parallel with the 5-gauss horizontal field. The differences in Table II between the variances at 30° and 0° are statistically significant as determined by the test ($P < 0.01$), as is also that between 30° and 90° ($P < .05$).

Table III

*Variances and mean paths*

| With magnet | | | Controls | |
|---|---|---|---|---|
| Orientation | Variance | Mean path | Variance | Mean path |
| 0° | 36.20° | 23.5° | I 19.08° | 24.7° |
| 15° | 34.46° | 23.9° | | |
| 30° | 31.05° | 25.4° | II 26.80° | 25.1° |
| 45° | 44.40° | 26.5° | | |
| 60° | 32.82° | 27.9° | III 22.57° | 25.2° |
| 75 | 40.06° | 28.9° | | |
| 90° | 44.20° | 29.5° | IV 25.95° | 25.1° |

### Response of Paramecium to a 1.3-Gauss Field

It was of interest to learn whether a single-celled form exhibited such orientational responses. *Paramecium caudatum* was permitted to escape from the exit of a magnetic-South-directed, minute, funnel-shaped, aluminum corral set in the center of a 3¾-inch round Petri dish containing water 2 mm. deep. The corral exit was carefully entered over the origin of a polar coordinate paper grid (Fig. 9A). The grid was, in turn, set on the platform of a stereoscopic microscope and illuminated weakly from below by a 7½-watt incandescent lamp with opalescent glass. Between the lamp and the microscope platform was a water filter for heat absorption, and an opaque screen with a circular opening carefully centered under the corral exit. The whole apparatus was placed in a darkened enclosure. With this arrangement, the emerging paramecia were clearly silhouetted for observation.

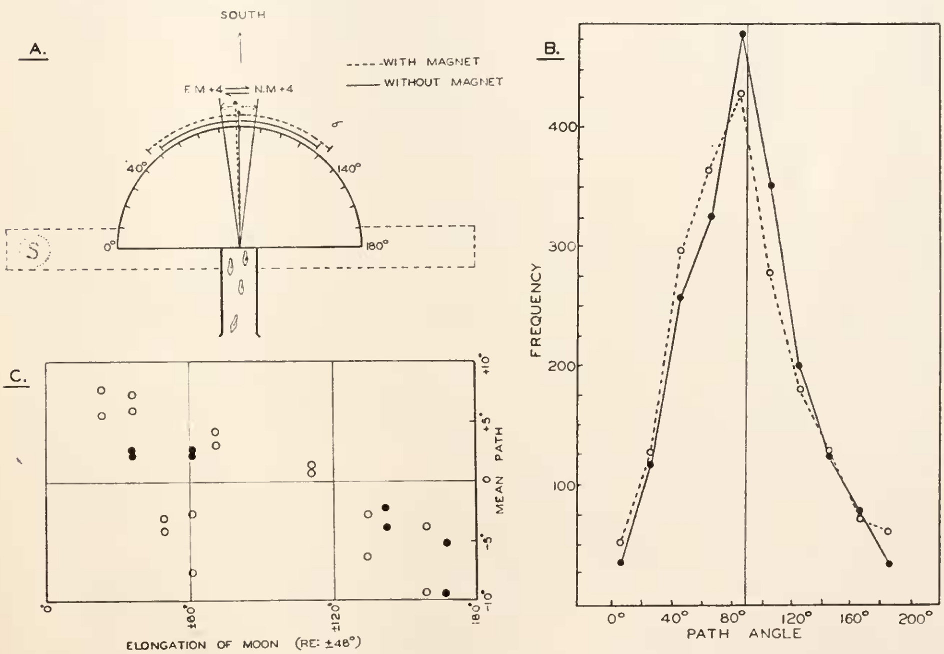


FIGURE 9. (A) Orientation of the apparatus and of the experimental bar magnet for the *Paramecium* study, illustrating mean paths in the natural and experimental field, the range of mean paths in the apparent monthly cycle, and the standard deviations of the paths. (B) The distribution of paths of *Paramecium* in the earth's magnetic field alone (solid line) is compared with the distribution when the experimental 1.3-gauss, E-directed field is superimposed (broken line). For purposes of this illustrated comparison, the values for the controls were increased proportionately to make the total number equal to that of the experimental series. (C) The relationship between mean path and elongation of moon treated as deviations from the fourth day after new moon.

Each experiment consisted of alternating observations of (1) a few paramecia making their exit in the earth's magnetic field alone with (2) a few fully comparable exits when the magnetic field was altered by an 18-centimeter Alnico bar magnet, placed horizontally and centered directly below the exit with S-pole pointed East.

The distance of the magnet was such that the strength of the horizontal East-directed component was 1.3 gauss. This horizontal strength is about eight times the earth's H component; the total field is only two to three times the earth's total field, F. Although the microscope base was predominantly constructed of non-ferromagnetic materials, two pairs of steel screws symmetrically placed two to three inches east and west were present and the microscope arm was of ferrous metal. However, that the earth's field and experimental 1.3-gauss field were not significantly distorted was assured by placing a small compass in the place of the corral. The angle of deviation of the paths from the initial southward course was determined by the point at which the animal crossed a circle perimeter with 0.5-inch radius, centered at the origin of the grid.

Between the dates February 14 and March 9, 1961, a total of 3774 individual paths were observed, 1762 in the earth's field and 2012 in the experimental, magnetic field. These data were obtained exclusively between the hours 8:30 A.M. and 4:30 P.M., but chiefly between 2:30 and 4:30 P.M. The observations were made on 12 different days during the 24-day period of study.

There was a strong positive correlation between the mean paths of the samples run in the experimental magnetic field and the control samples on the same day ($r = 0.86 \pm 0.09$). There was also a highly significant difference between the variances of paths under the two magnetic conditions. The stronger, imposed East-West field produced a highly significantly greater amount of deviation of paths from South, both clockwise and counterclockwise. Expressed as standard deviation of paths, a value of $37.7 \pm 0.638°$ was found for the earth's field and $41.3 \pm 0.656°$ for the stronger, E-W oriented one. There was, therefore, clearly an influence, highly statistically significant, of the field-strength change, whether one ascertained probabilities by the F or t test ($F = 1.20$; $t = 3.93$).

Analysis of the data indicated that there was no significant difference between the mean path of those paramecia in the 0.17-gauss South-directed earth's field and of those in the East-directed 1.3-gauss field.

However, the comparative distributions of frequencies of paths for paramecia in the 1.3-gauss E-W field and in the earth's South-directed field alone are shown in Figure 9B. Using a Chi-square test to measure the probability that the two samples were drawn from the same population, a value of $\chi^2 = 29.95$ with 9 degrees of freedom was obtained ($P < .001$). Inspection of the figure suggests this highly significant difference to be a consequence in large measure of an overall shift of the crown of the distribution curve for the animals in the experimental field to the left of that of the controls in the earth's alone.

In view of the previously demonstrated synodic monthly fluctuation in mean path of both mud-snails and planarians, the *Paramecium* data were examined for the possible existence of a comparable periodism. Inspection of the mean paths as a function of time revealed a distinct suggestion that the paramecia, too, displayed a monthly fluctuation. The inspection suggested that maximum clockwise turning was occurring for paramecia about four days after new moon (Feb. 19) and maximum counterclockwise turning about four days after full moon (March 6). In fact, computed correlations, with elongation of the moon considered as an intrinsic time series, corroborated this suggestion. With elongation of the moon expressed as $\pm 180$-degree deviation from four days after new moon ($+48.8°$) the value of the coefficient of correlation, r, was $0.76 \pm 0.09$, $N = 24$. This was higher than that found in any other phase relationship with respect to the natural monthly cycle (Fig. 9C).

Since only a 24-day period (ca. 290°) was involved in the study, it is obviously not possible to conclude with great confidence that the period of this long-cycle fluctuation in mean path was, indeed, a monthly one. However, that it probably was a monthly one is suggested since extremes of both clockwise and counterclockwise response appeared to occur within the 24-day period, and the interval between the estimated maximum clockwise and the estimated maximum counterclockwise turning seemed clearly consistent with it being 180°. Indirect support for such a cycle is considered to come from the now far better established occurrence of this period in comparable orientations of the two other previously investigated species.

Just as for the snail and planarian, one very conspicuous influence of magnetic field is upon the turning tendency in the field, without respect to whether it is clockwise or counterclockwise. It seems probable that the character of response of paramecia to an increase in magnetic field will be found, as in the other two kinds of animals, to be functions of (1) times of lunar and solar days, and their interference derivative, the synodic month, and (2) the direction of the H-component of magnetism with relation to the long axis of the body.

## Discussion

Several considerations were involved in planning the present investigation. First, to be of significance under natural conditions, the organism must exhibit responsiveness to field strengths of the order of magnitude of the earth's. Any perceptive system of this sensitivity could well be expected to display little or no resolving power for fields differing greatly in strength from the earth's. Therefore, only weak fields were investigated. Secondly, to be maximally adaptive the organism would be expected to be able to differentiate the compass direction of these very weak fields. Thirdly, any response obtained might be expected to vary in a "clock-regulated" manner. And lastly, to account for a number of still unexplained biological phenomena, the responses must be postulated capable of sign reversal. For this study, the orientation of whole organisms was considered to constitute the most sensitive method for assaying any possible biological resolution of magnetic field strength and direction.

To reduce the problem to its simplest form we attempted to learn the nature of orientational tendencies or pressures in samples of a population subjected initially to enforced orientation in a highly restricted unit of space, to horizontal magnetic fields, both natural and experimental. As we have seen, the general method consisted in inducing, or permitting, organisms initially to travel in an arbitrarily decided magnetic compass direction in the earth's natural field and in experimentally altered magnetic fields, and assaying the amount the animal's paths have deviated, clockwise or counterclockwise, from the initial path after an arbitrary constant short distance was traversed.

In this present study the experimental fields that were used were only those obtained in the number 2 position of a straight bar magnet, in order that maximum simplicity could be achieved. By this means it was possible to alter at will the horizontal components of magnetism without significant change in the ambient vertical component, which throughout the experimental studies remained the earth's natural one. Furthermore, with the path of the worms being assayed for only a relatively short distance over the number 2 position, and in a plane parallel to that occupied by the magnet, insignificant field-strength differences were present within any given experimental field. The earth's magnetic field is essentially a homogeneous one. The fields that were employed in this study were similarly relatively homogeneous. The field gradient was less than ½ gauss per centimeter.

In those experiments in which the magnet was rotated in a horizontal plane in the earth's field there was a change not only in direction of the imposed horizontal component, but there was also a difference in its strength as the magnet's contribution supplemented or antagonized the geomagnetic one. No attempt was made to compensate for this. For the 10-gauss field, for example, this involved about a 3½% range and for the 5-gauss one, nearly a 7% one. However, these field-strength differences can not alone account for the resolution of the direction of horizontal vector by the organisms since field-strength differences many times larger than these small percentages did not duplicate the influences of small changes in field orientation. Experiments are now in progress which are expected to provide information as to the relative roles of changes in the strength and direction of the horizontal vector.

The problem of resolving organismic responses to weak magnetic fields is compounded by the recent discovery that mud-snails are extraordinarily sensitive to differences in the horizontal vector of electrostatic field (Webb, Brown and Schroeder, 1961). Furthermore, *Dugesia* too has such responsiveness and displays a "compass direction effect" in response to very weak electrostatic fields which is, at least in good measure, independent of the magnetic-compass response (Brown, 1962b). In the present studies, no attempt was made to control the ambient geoelectrostatic field and its changes.

The implications of findings such as the ones reported here, and ones described earlier for the mud-snail, *Nassarius* (Brown, Brett, Bennett and Barnwell, 1960; Brown, Webb and Brett, 1960; Brown, Bennett and Webb, 1960), are great not only in providing an additional parameter to contribute toward the solution of such stubborn problems as those of living clocks and navigational systems of organisms, but also for the problem of regulation within living systems in general. With biological systems possessing astounding sensitivity to such weak magnetic fields, the possibility exists that magnetism may normally play a role in general, organismic integration, either directly or through the biological clock system.

The kinds of magnetic responses described here for *Dugesia* appear not to be specific for this flatworm but simply to represent a general property of living things. The potential of such a sensitivity, with capacity to resolve strength and directional changes, when incorporated into adaptive behavioral systems as an informational input seems tremendous. Search for possible important adaptive roles of these extraordinary biomagnetic sensitivities will probably be very rewarding.

## Summary

1. The orientational response of the planarian, *Dugesia,* at a given time of solar day undergoes what appears to be a semi-monthly or monthly fluctuation, probably

a consequence of the possession of a lunar-day rhythm in response to some compass-directional factor.

2. The monthly rhythm in *Dugesia* is modifiable by a weak magnetic field.

3. The monthly rhythm appears to undergo an annual modulation.

4. *Dugesia* exhibits a response to weak magnetic fields in the range of 0.17 to 10 gauss.

5. *Dugesia* differentiates between a horizontal field parallel to the long axis of the body and a field at right angles, and between N and S poles, and, furthermore, is able to resolve intermediate angular orientations of field with remarkable precision.

6. The response of *Dugesia* alters its character in passing from a field close to the earth's strength to one as little as 10 gauss, suggesting the perceptive mechanism to be specifically adapted to such a weak field as the geomagnetic one.

7. There is suggestive evidence that the protozoan *Paramecium* also responds to very weak magnetic fields.

8. Some possible roles for organisms of such astounding responsiveness to very weak magnetic fields are discussed briefly.

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